

# Motor Demonstration Using a Hand-Cranked Genecon

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A Genecon is an inexpensive hand-cranked dc electric generator. You can use it to charge a one-farad supercapacitor.<sup>1</sup> If you stop cranking the handle, the capacitor will discharge, sending a current into the Genecon and thereby causing the handle to start turning as an electric motor. How does the current direction compare before and after you stop cranking the handle? How does the direction of the turning of the handle compare before and after you stop cranking the Genecon?

A Genecon has a set of internal gears, coils, and commutators (some of which can be seen inside the translucent case in Fig. 1) that generates an approximately steady dc voltage for a given rate of cranking of the handle. To visualize the degree of rectification, connect the Genecon across a  $51\text{-}\Omega$  resistor and then connect the ends of the resistor to an oscilloscope with a  $1\text{-M}\Omega$  input impedance.<sup>2</sup> A photograph of the resulting trace is presented in Fig. 2 while the crank is being turned at a rate of about 1 Hz. Riding on an average dc voltage of approximately 3 V is a superimposed ripple of 1 V peak-to-peak having a 2-ms period. As one turns the handle faster, the dc voltage, ripple frequency, and ripple voltage all increase linearly,<sup>3</sup> as the careful measurements in Table I verify. The ripple is fast enough that it gets averaged out on the timescale of seconds of the demonstrations presented here and it therefore can be ignored.

As described in Sec. 11 of the CASTLE Student Guide,<sup>4</sup> supplying a current to a Genecon (for example, by connecting it to a battery) will cause it to function as a motor and turn the handle. Robert Ehrlich<sup>5</sup> suggests connecting a Genecon to a 1-F capacitor instead of a battery. Charge the capacitor by cranking the handle, say, in a clockwise direction at a moderate speed of turning (to stay under the typically 5-V maximum rating of commercially available “supercapacitors”). Connect an ammeter (on the 200-mA dc range) with the polarity of the leads and the rate of cranking of the Genecon adjusted until a charging current of about +100 mA is observed. Project the ammeter display onto a screen using a document camera, so the whole class can see it. When the handle is released, the capacitor begins to discharge, and accordingly the ammeter current then reads *negative*. Surprisingly, the handle of the Genecon, which is now operating as a motor, continues to turn in the *same* direction as it did when you were cranking it to charge the capacitor. That is, if it was being turned clockwise to generate a positive charging current, then after release the handle will still turn clockwise, even though the current is now in the opposite direction! (The ammeter contributes non-negligible electric losses in the circuit, so it is a good idea to remove the ammeter from the circuit, after having demonstrated the sign change in the current for charging and dis-

charging of the capacitor. Directly connecting the Genecon to the capacitor will make the motion of the motorized handle significantly faster than with the ammeter still in the circuit.) Show students that the direction of rotation of the handle does not reverse even if you temporarily freeze the handle in



Fig. 1. Photograph of a Genecon (in translucent blue with a white handle) connected to a 1-F supercapacitor (in green).

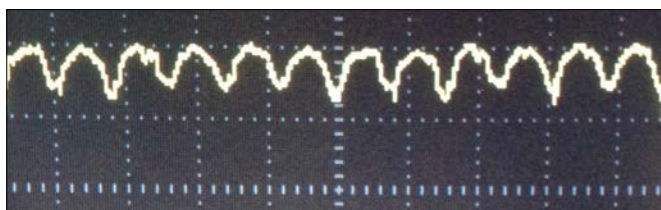


Fig. 2. Voltage across a  $51\text{-}\Omega$  resistor connected to a Genecon when the handle is cranked with a period of about 1 s. The vertical axis is voltage in 2 V per division (with 0 V along the bottom line of vertical dashes) and the horizontal axis is time in 2.5 ms per division. Owing to the gearing, the coils spin much more rapidly than the handle.

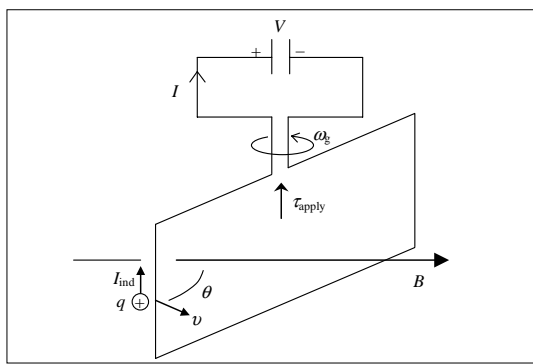
Table I. Frequency at which the handle must be turned (as computed by timing 20 revolutions) to give the indicated average output signals in 1-V steps, together with the ripple voltage and frequency (measured using the oscilloscope horizontal and vertical cursors). Plotting any column against any other gives a linear graph that passes through the origin. These data were collected without the  $51\text{-}\Omega$  resistor and are accurate to  $\pm 5\%$ .

average dc voltage (V)	cranking frequency (Hz)	ripple peak-to-peak voltage (V)	ripple frequency (Hz)
1	0.40	0.42	130
2	0.83	0.78	230
3	1.23	1.04	360
4	1.69	1.36	450
5	2.04	1.68	560

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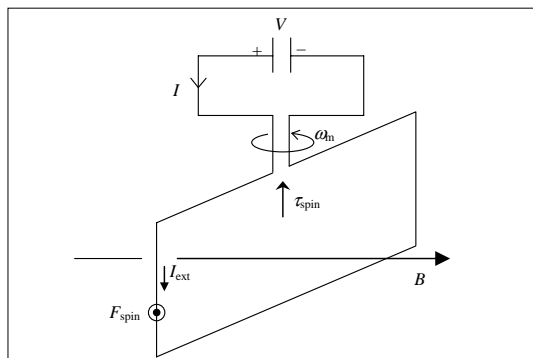
its orientation after you stop cranking it, just to demonstrate that it is not turning because of any “rotational inertia” you imparted to the handle when you were charging up the capacitor. In other words, briefly lock the handle with your fingers after you stop turning it, show the class there are no gears or other parts continuing to turn inside the translucent case, and then release the handle to see the motor effect.

Ehrlich states that this constancy of the direction of rotation can be explained using the “right- and left-hand rules” for generators and motors.<sup>6</sup> That explanation is cryptic, so it is worthwhile expanding on the details as follows. For simplicity, initially represent the generator coil as having only a single loop and neglect mechanical friction in the bearings, so that the only source of dissipation comes from the electrical resistance  $R$ . Start with the generator, as sketched in Fig. 3. Spin the coil at angular speed  $\omega_g$  by applying torque  $\tau_{\text{apply}}$



**Fig. 3. The Genecon operating as a generator to charge up the capacitor via net current  $I$ .**

with your hand. At the instant the coil has the indicated orientation, its front vertical segment has velocity  $v$  that makes angle  $\theta$  with the permanent magnetic field  $B$  (chosen to be horizontally rightward in the plane of the page). Consider a positive charge  $q$  in this segment: it is driven upward by the  $qv \times B$  magnetic force. (Actually it is conduction electrons that are mobile and that are driven downward, but the effect is the same.) Consequently, an induced current  $I_{\text{ind}}$  is generated that charges the capacitor up to some potential difference  $V$ . (Although the split-ring commutator is not drawn, there must be one to avoid reversing the sign of the induced current every half-cycle.<sup>7</sup>)



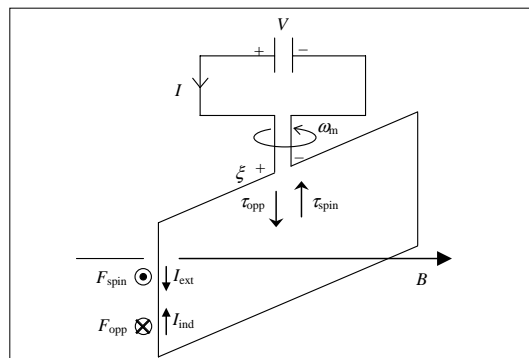
**Fig. 4. The Genecon operating as a motor powered by net current  $I$  as the capacitor discharges.**

Next consider the motor at the same instant of orientation as the generator, as sketched in Fig. 4. The potential difference  $V$  of the capacitor drives an external current  $I_{\text{ext}}$  in the coil, opposite in direction to the induced current in Fig. 3. This current in the permanent field  $B$  gives rise to the indicated force  $F_{\text{spin}} = I_{\text{ext}} L \times B$  on the front segment of length  $L$  (where vector  $L$  is in the direction of the current) and hence to a torque  $\tau_{\text{spin}}$  that spins the coil at angular speed  $\omega_m$  in the same direction as in Fig. 3.

The preceding two figures explain why the direction of rotation is the same for the generator and the motor. However, the following puzzling questions may now occur to a thoughtful observer.

- Since the motor handle turns in the same direction needed to charge up the capacitor, why doesn't the capacitor get *spontaneously recharged* as the motor runs?
- Why haven't we created a perpetual motion machine?
- Isn't Lenz's law supposed to prevent this kind of apparent violation of conservation of energy?

To resolve this puzzle, one can re-examine either the generator or motor and take into account the back emf<sup>8</sup>  $\xi$ . Since the idea is similar in both cases, it suffices to consider just



**Fig. 5. A more complete sketch of the Genecon operating as a motor than the simplified version in Fig. 4.**

the motor. Figure 5 again shows current  $I_{\text{ext}}$  driven in the Genecon by the external capacitor, along with the force  $F_{\text{spin}}$  and torque  $\tau_{\text{spin}}$  on the coil that results from the interaction of that external current with the permanent magnetic field  $B$ , just as in Fig. 4. At the same time, however, one can also consider positive charges in the front segment of the coil to be driven upward, as in Fig. 3, which thus induces a back current<sup>9</sup>  $I_{\text{ind}}$ . Since that current is reversed in direction compared to  $I_{\text{ext}}$ , the resulting magnetic force  $F_{\text{opp}}$  and torque  $\tau_{\text{opp}}$  on the coil are opposite  $F_{\text{spin}}$  and  $\tau_{\text{spin}}$ , respectively. Noting that the induced current  $I_{\text{ind}}$  would flow clockwise in the upper loop (containing the capacitor), the moving coil is thus generating an emf  $\xi$  as if it were a battery whose + and – terminals are as labeled in Fig. 5 next to the vertical pair of wires connecting the capacitor circuit loop to the motor coil. (Remember that if you connect a wire loop to a battery, current flows from the positive to the negative terminal in that

loop outside the battery, but it is driven from the negative to the positive terminal inside the battery.)

The net clockwise current  $I$  in Figs. 3 to 5 is thus given by the difference between the induced emf and the capacitor voltage divided by the resistance of the circuit,

$$I = \frac{\xi - V}{R}. \quad (1)$$

For the motor,  $V > \xi$  so that the net current  $I$  is counterclockwise in Fig. 5, as labeled near the capacitor. On the other hand, for the generator,  $V < \xi$  so that the net current  $I$  is clockwise in Fig. 3. If the Genecon consisted of a single flat coil of  $N$  windings, Faraday's law states that the induced emf would be given by the negative time derivative of the total magnetic flux  $NBA \cos \theta$  (where  $B$  and  $\theta$  are as labeled in Fig. 3, and  $A$  is the area of the coil) so that

$$\xi = -N \frac{d}{dt}(BA \cos \theta). \quad (2)$$

But the orientation of the coil varies with time  $t$  according to  $\theta = \omega t$  (assuming one defines the initial angle of the coil to be zero), where  $\omega$  is the angular speed of the rotating coil. Substituting that expression into Eq. (2), one obtains

$$\xi = B\omega (NA |\sin \omega t|), \quad (3)$$

where absolute value bars have been added around the sine function to account for the split-ring commutator. Suppose the quantity in parentheses is averaged over time. The mean value of  $\sin \theta$  as  $\theta$  increases from 0 to  $\pi$  (for each half-cycle) is

$$(|\sin \theta|)_{\text{avg}} = \frac{1}{\pi} \int_0^{\pi} \sin \theta d\theta = \frac{2}{\pi} \quad (4)$$

so that the time-average of Eq. (3) becomes

$$\xi_{\text{avg}} = B\omega K, \quad (5)$$

where  $K \equiv \frac{2}{\pi} NA$  is called the motor constant.<sup>10</sup> As inspection of Fig. 2 suggests, a Genecon actually has multiple coils in it arranged uniformly around a  $2\pi$  rotation of the armature, to increase the frequency and reduce the peak-to-peak voltage of the ripples compared to what one would get for a single coil. Consequently  $K$  is some other numerical multiple of the geometrical factor  $NA$  than  $\frac{2}{\pi}$ , but the idea remains the same. One can also include the gearing ratio between the handle and the armature in  $K$ , so that  $\omega$  refers to the directly observable angular speed of the handle rather than that of the coils.<sup>11</sup> This predicted direct proportionality between  $\xi_{\text{avg}}$  and  $\omega$  has been experimentally verified for a low-power dc motor<sup>12</sup> and is supported by the data in Table I.

Equation (1) implies that the net current is zero on average when  $\xi_{\text{avg}} = V$ . According to Eq. (5), that occurs at a "neutral" angular speed of the handle of

$$\omega_0 = \frac{V}{KB}. \quad (6)$$

To run the Genecon as a generator, one must turn the

handle at a greater speed,  $\omega_g > \omega_0$ . On the other hand, it will run as a motor at a speed lower than this neutral rate,  $\omega_m < \omega_0$ . One could therefore say that relative to a reference frame rotating at the neutral angular speed, the motor handle does in fact turn in the *opposite* direction compared to the direction of turning of the handle when being used as a generator, which is a satisfying conclusion. In the demonstration of connecting a Genecon directly across a capacitor, one indeed observes that one has to crank the handle significantly faster to charge the capacitor than the handle turns as a motor after you let it go. This observation leads to one final demonstration worth showing students. Connect a voltmeter on about a 5-V dc scale across the capacitor. Crank the handle until the capacitor charges up to, say, 1 V. By now easing up on the rate of cranking, one can hold the capacitor voltage approximately constant at that value. One is then turning the handle at the neutral speed corresponding to  $V = 1$  V in Eq. (6). Estimating the period at which you are cranking the handle thereby provides a means of determining the Genecon constant  $KB$ . You are neither charging nor discharging the capacitor at this rate of turning, so from energy conservation you are then directly feeling the mechanical power your wrist muscles must expend to counter the dissipation into thermal energy in the bearings of the Genecon. Dividing that power<sup>13</sup> by the neutral angular speed gives the frictional torque  $\tau_f$  which could be included in a yet further improved version of Fig. 5 by adding it to  $\tau_{\text{opp}}$ .

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## References

1. A Genecon costs about \$50 and a 1-F capacitor about \$35. They are available from numerous scientific suppliers by searching the web.
2. The resistance of a Genecon is  $10 \Omega$  and can be connected directly to an oscilloscope or voltmeter without the  $51\text{-}\Omega$  resistor. However, the resistor attenuates the sharp noise spikes near the troughs in Fig. 2 so that they are barely visible.
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4. The CASTLE ("Capacitor-Aided System for Teaching and Learning Electricity") Student Manual is freely available at <http://ftp.pasco.com/Support/Documents/English/EM/EM-8624A/2009/>. For further details about CASTLE, see M. S. Steinberg and C. L. Wainwright, "Using models to teach electricity: The CASTLE project," *Phys. Teach.* 31, 353–357 (Sept. 1993), and E. P. Mosca and M. L. DeJong, "Implications of using the CASTLE model," *Phys. Teach.* 31, 357–359 (Sept. 1993).
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